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A CALL FOR FDM DESIGN RULES TO INCLUDE ROAD DEPOSITION

Fornasini, Giacomo; Schmidt, Linda C.
University of Maryland, United States of America

Abstract

The deposition paths, or roads, used to create FDM parts area a critical factor in determining part performance. In some cases, such as the FDM machines discussed in this work, there are no designer options to control road patterning, making it a hidden constraint in the design process. Even if the option is given, the designer must be aware that it is a variable. In either case, deposition road patterning is not something that can be taken for granted when designing parts. A new level of DfFDM guideline development must be implemented if AM is to reach the level of universality as other traditional machining methods.

Keywords: Design practice, Design methods, Process modelling, Additive manufacturing

Contact:
Giacomo Fornasini
University of Maryland, College Park
Mechanical Engineering
United States of America
giac1215@terpmail.umd.edu

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1 INTRODUCTION

Since its advent in the 1980s, additive manufacturing (AM) technology has matured and expanded incredibly into new materials and applications. AM capabilities have exceeded the original scope of prototyping, moving to become a method for creating end-use parts. This is due to the continual advance of AM research and technology. AM development is motivating commercial and educational adoption of the technology. The anticipated shift to commercial use of AM parts and the rising importance of AM technology in educational settings drives the need to understand all relevant design for AM (DfAM) requirements for current and future part designers.

Attune to the national emphasis on additive manufacturing, many universities have created spaces where students can go to learn about and use AM technology for both academic and personal projects. Some universities are also expanding their fab labs to include more advanced equipment, such as metal 3D printers. This shows that demand for AM technology is growing, and AM is something worth investing in for future engineers and professionals. Fused deposition modelling (FDM) machines are the most common AM machines in use. FDM uses a heated nozzle to deposit a fused polymer filament into layers that make up the part. The relatively cheap cost of material and varying sizes of FDM machines makes this process a common choice for home, office, and educational use.

FDM printers require stereolithography (STL) file inputs that are processed by machine specific slicing software to create a stack of two-dimensional part cross-sectional layers, each layer is generating the path that the material deposition nozzle will follow. The designer of a FDM part is not likely to be aware of the deposition pathways (called roads) determined by the slicing software, nor is a designer likely to be aware that there are non-trivial differences in deposition pathways generated for the same part made on two different FDM machines. There is such variety between FDM printers that creating a list of design rules is not enough to exploit the full potential of this new technology.

This paper will illustrate that a general understanding of the FDM process in creating part layers does not convey enough information to design a part with specific performance characteristics. FDM deposition road patterning is not something that can be taken for granted when designing parts. A new level of DfFDM guideline development must be implemented if AM is to reach the level of universality as other traditional machining methods.

2 GEOMETRY RULES ON THE PROCESS LEVEL

The greatest advantage of AM technology is the ability to make single parts with complex internal geometries that were previously impossible with traditional machining. However, this ability leads to more difficulties in developing design rules. In traditional machining, individual "parts" are made from a single block, from which material is removed to yield the final part. The performance of the finished part is most greatly influenced by the material used and the design features selected by the designer. The performance is only minimally influenced by processing of the part. With traditional machining, most of the defects that occur during processing can be corrected through post-processing such as heat treatment.

In the case of FDM, the starting point is not a uniform block of material, but rather, a single filament. The process by which that material is deposited and the internal geometry of the filaments have a much more significant effect on the performance characteristics of the part than the material characteristics of the filament. When roads and their geometries are controlled solely by machine software many resulting processing effects cannot currently be designed around, or designed for (in the language of design for manufacturing).

In fact, some design rules that would normally increase performance in traditionally machined parts could actually lower the performance of a part made through AM. For example, the highest stress concentrations within a part usually occur at sharp corners because there are forces acting in multiple directions at that point. A way to design around this issue is to avoid sharp corners, and instead use rounded edges (Dally, 2010). However, due to the way that an FDM program dictates the orientation of the roads, there is actually an increase in stress concentrations when the part is created with what should be stress-relieving features (Ahn, 2002). Without understanding this road geometry more clearly, the process by which parts are made can affect the part more than their design.

The road deposition algorithms control layer deposition in FDM machines, and these programs can cause differences even within the same printer and part. For example, just the orientation of the part can cause significant differences in the amount of time and material needed to build it (Teitelbaum, 2009). If the differences within a single machine can vary so much, it may vary even more between different machine using different slicers.

2.1 Previous Work in Developing FDM Build Guidelines

As FDM technology became more and more commonly used to create prototypes and end-use parts, the need to develop design for fused deposition modelling (DfFDM) rules became evident. Design for Manufacturing rules for traditional machining have been commonplace for a few decades. Some researchers extended the DFM work to consider hybrid artifacts with machined parts and shape deposition parts. One such researcher (Binnard, 1999) introduces a design method with some rules for shape deposition part fabrication. The literature shows that the body of FDM work has been expanding recently. At the CIRP Conference on Manufacturing in 2012, French researchers developed some rules for creating laser-sintered parts. Vayre et al. (2012) found that changes in acceleration of the laser caused imperfections in parts. They suggested to use rounds rather than sharp edges, which would allow the laser to have a more consistent speed. This is similar to the commonly accepted design rule developed for injection molding, where sharp corners can have similar problems when the liquid polymer is pushed into the cavity. They go on to develop a set of rules for designing parts that will be additively manufactured, including analysis of the specification, developing basic shape, setting parameters, and parametric optimization. Each step takes the general design rules for developing a part and modifies it specifically for laser sintering AM.

The Direct Manufacturing Research Center (DMRC) at the University of Paderborn, Germany began a three year project in 2010 to develop a comprehensive set of design rules for basic components and features common to many parts. DMRC researchers studied these rules for different AM technologies, including laser sintering and FDM. Their premise was that, as is true of injection molded parts, most complex parts can be broken down to a series of more basic shapes and transitions. These shapes and transitions would be the target of the design rules. The final project consisted of about 60 different shapes and transition elements, each with specific rules for designing them to be as efficient as possible. A follow-up project has begun that intends to test and expand these rules further to include a broader set of machines and process parameters (Guido, 2013).

One AM process parameter that has been studied to a lesser degree is that of deposition road geometry. Roads are the deposition paths created by the moving nozzle. The nozzle moves along these roads, depositing material along them. A study on the resultant road geometry was done for tissue engineering by Zein et al. (2001). Zein and his colleagues studied the effects of orientation and alternating of roads on the porosity and mechanical properties of the scaffolds of 3D printed tissues. In order to see differences between tissue samples, SEM images of cross-sections of the samples perpendicular to the road patters were taken. The results showed clear differences in structure depending on the orientation of each layer. Zein et al. (2001) observed correlations between layer orientations and properties of the tissue. Pores created between layers were larger in the scaffolds with layers alternating between 0 and 90° than in ones with layers alternating between 0°, 60°, and 120°. The channels between filaments in each layer were found to have the opposite correlation. The 0 and 90° alternating scaffolds were also found to have a higher stiffness than the 0°, 60°, and 120° scaffolds, but similar yield strength.

In a more general work that considered the impact of road patterns on material used and build times, Teitelbaum began researching how the same part can turn out differently depending on how it is processed by the slicer software (2009). Teitelbaum created several test parts, which he ran through StratasysEX slicer software at different build angles. The results showed that orienting the parts at 45° statistically resulted in less material use and faster build time (Teitelbaum, 2009).

The brief discussion of the literature shows that rules aimed to help designers create parts that take into account the advantages and disadvantages of AM technology have been developed. However, there is still an aspect that is not taken into account with these design rules: namely, the specific deposition paths that a printer uses to create the part. In the Teitelbaum research, the orientation of the deposition path can affect the amount of time and material needed to build a part (2009).

3 METHOD FOR EXPLORING ROAD GEOMETRY

The exploration of the effects of road geometry began by creating parts on a Dimension sst 1200ES 3D printer, similar to that studied by Teitelbaum (2009). The parts were set to have the highest density in-fill, which – in an ideal situation- create a completely solid part. Two copies of the same part were built: one oriented vertically with respect to the printer's X-Y coordinate system, and one oriented 45° relative to that X-Y coordinate system. After printing was completed, we observed the part under a high-resolution microscope. The Dimension printer is known to lay down material at alternating 45° and 135° angles (with respect to the x-y plane of the build plate). This is seen in Figure 1, where the part printed along the vertical axis shows roads that follow a 45° path for the main area of the part. Because of this, orienting parts at 45° shows a 90° road pattern. This allows the roads to follow contours of rectangular shapes more closely, explaining the reduced time and material use found by Teitelbaum (2009).

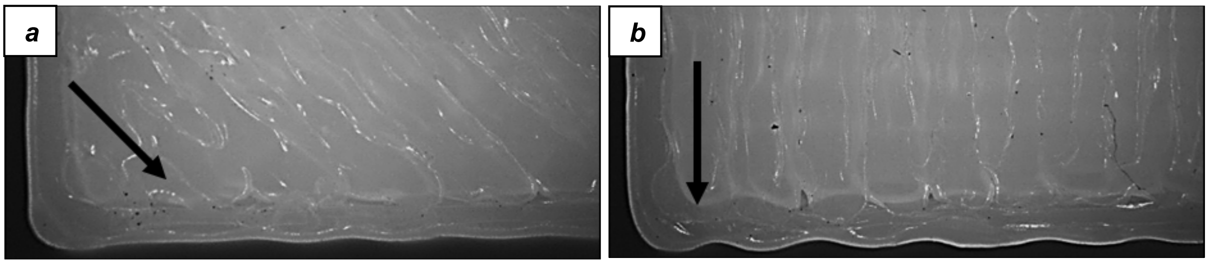


Figure 1. Top views of the printed parts: a) part printed vertically b) part built at 45° offset

3.1 Breaking In: Exploring the Internal Structure of Printed Parts

Images of the part surfaces (Figure 1) give some insight into the results found by Teitelbaum (2009). The Dimension printer deposits roads that follow 45° paths with respect to the x-y coordinate system of the printer's build plate. The images in Figure 1 only reveal the external road deposition behaviour of the printer. Learning about internal road structures requires a cross-sectional view of the parts. Similar to Zein et al.'s (2001) procedure, the parts were placed in liquid nitrogen for 5 minutes, until thermal stability was reached. They were then cracked using a metal shear to give some directionality to the break.

Figure 2 displays the fractured parts showing how the fracture surface orientations varied. Even though the force was applied along the same trajectory, both fracture surfaces aligned with internal road orientations.

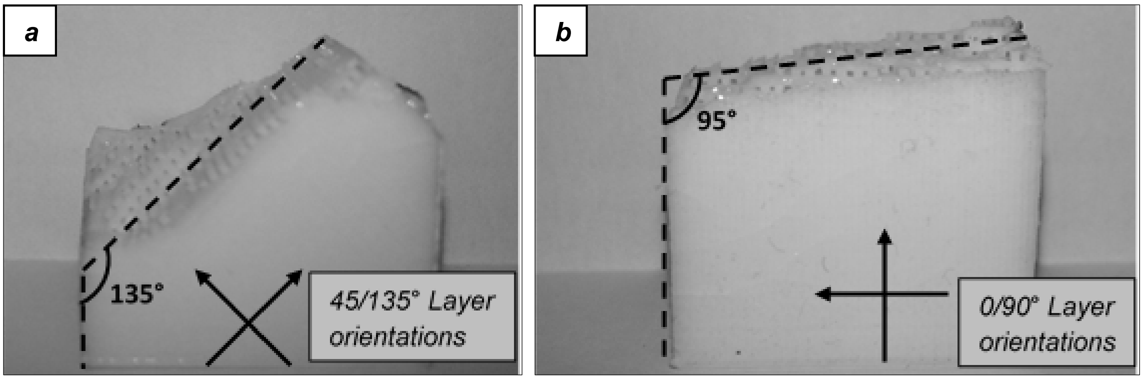


Figure 2. a) part with alternating 45 and 135° deposition paths shows a diagonal fracture plane b) part with alternating 0 and 90° deposition paths shows a horizontal fracture plane

The fractured parts were placed under a high resolution microscope to record images of the fracture surfaces (Figure 3). The images highlight interesting characteristics of the differently printed parts. Figure 3b shows a complex structure within the part that cannot be inferred by looking at the finished part surfaces. It is a hidden structure that the user cannot control, even by modifying the in-fill settings. The gaps present within the structure can have an impact on part performance under loading. Potential impacts fall outside of the factors that can be designed for with current design rules.

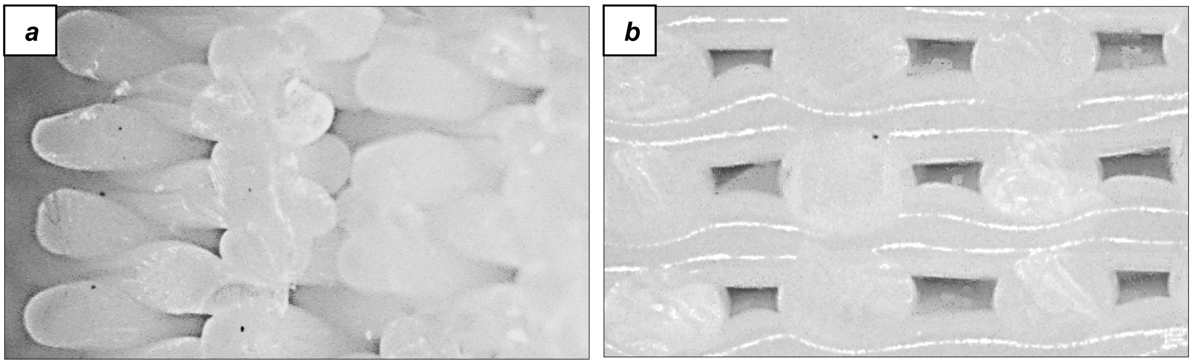


Figure 3. Cross-sections of parts along the length of the rectangle a) part with alternating 45 and 135° deposition paths shows crossed ends b) part with alternating 0 and 90° deposition paths shows grid-like structure

3.2 Roadmaps: Taking a Closer Look at Slicer Software

In order to compare the road geometries of different printers, it was necessary to create 3D computer models and run them through the slicer software for each printer. The road trajectories that make up the layers in a part depend on functions written into the slicer software. For this exploration, three printer models were selected that are readily available for home, office, or educational use. Their road deposition codes are not modifiable by the user, but are internal to the system. The printers and software used for this comparative analysis are a Dimension sst 1200es printer using StratasysEX software, a CubeX Trio printer using Cubify software, and a Makerbot Replicator 2x using Makerbot Desktop software.

Table 1. Printer Properties

Printer	Software	Build Size (mm)	Materials	Nozzles
Dimension sst 1200es	CatalystEX	254 x 254 x 305	ABS	2
Cubex	Cubify	230 x 265 x 240	ABS, PLA	3
Makerbot Replicator 2x	Makerbot Desktop	246 x 152 x 155	ABS, PLA	2

The part modelled was a rectangular block 100x30x20 mm in size, with through-holes of various sizes ranging from 1 mm to 20 mm in diameter (Figure 4). Observations were made primarily on the three holes in the bottom of the block shown in Figure 4.
The images in this section were obtained by running the slicer software on the test block with the 100mm side oriented in the horizontal direction (along the x-axis of the printer) The software generated the roads and layers needed to make up the part. Each slicer has a tool that allows the user to view the part at different slice heights. These slices show the roads that make up each individual layer. These layers were then recorded for closer study.

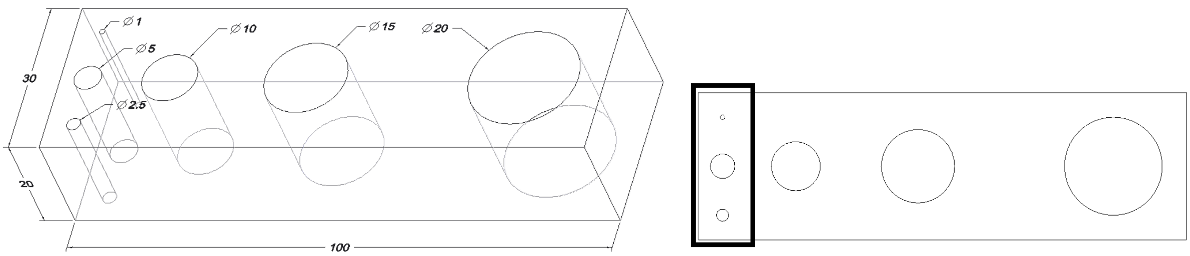


Figure 4. Model used for comparing software and printed parts and the area used for detailed views in the following parts

3.2.1 Perimeter Roads

The first comparison was done on perimeter roads. Perimeter roads are the roads that create the vertical walls of the part (i.e., the surfaces that are created along the z-axis of the build volume). Perimeter roads stack up to form (not quite planar) surfaces that will be visible from the outside of the finished part. For the test block, the perimeters consist of the external walls of the block and the walls

inside the holes. The purpose of the unique trajectories of these perimeter roads is to give a more uniform finish to external surfaces. This slicer accomplishes this by generating roads that trace the perimeter of the shape with a single, continuous road, regardless of the part geometry.
Figure 5 shows the planned trajectories of the sample part's perimeter roads in the Dimension printer. This is the simplest example of perimeter roads between the printers, because there is no variation between layers. Each layer has two parallel roads around each external feature.
The CubeX printer has two major differences from the Dimension. The first is that the number of roads is different. The Dimension has only two roads around each perimeter, while the CubeX at least three. The second difference is that the perimeter roads are not identical between layers. The four bottom layers have four perimeter roads, while the rest of the part has only three perimeter roads per layer (Figure 6).
The Makerbot Desktop program allows the user to set how many perimeter roads they want. This is not an option available on the other programs. The block model was processed several times with different settings, ranging from two to seven perimeter roads (Figure 7). Like the Dimension, the number of roads in the Makerbot part do not vary between layers.

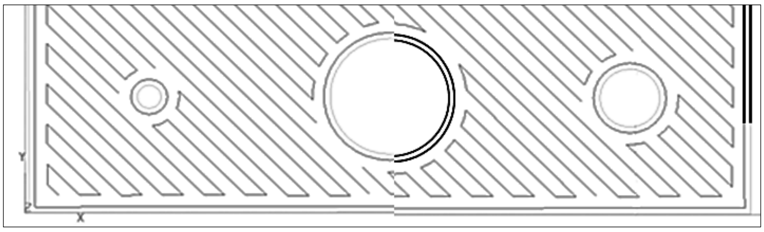


Figure 5. StratasysEX showing 2 outer paths around block and hole perimeters. The darkened lines indicate the 2 paths that become the surfaces of the part.

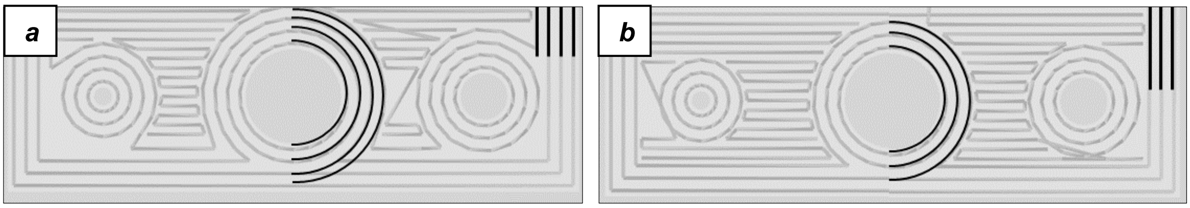


Figure 6. Cubify showing a) 4 outer paths on lower layer b) 3 outer paths on upper layer

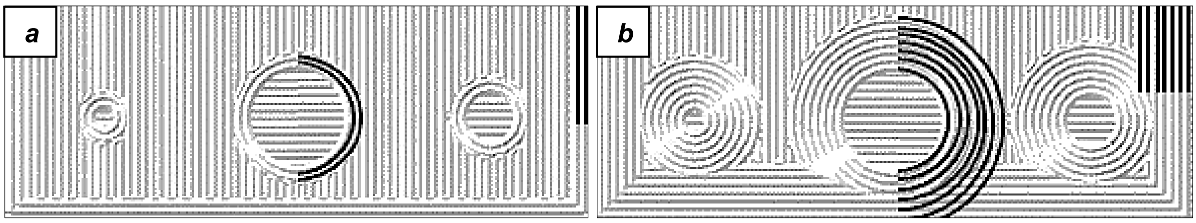


Figure 7. Makerbot Desktop with user-set perimeter roads a) 2 roads b) 7 roads

3.2.2 Fill Roads

The fill layers make up the main body of the part. The fill roads are deposited with a back and forth rastering motion, which fills the spaces between the perimeter roads to yield a semi-solid part. Due to the high percentage of the part that is made up by these fill roads, their orientation and patterns play a critical role in the performance characteristics of the part. As was already known, the Dimension fill roads alternate between 45° and 135° (relative to the x axis in the x-y plane of the build plate) as seen in Figure 8 (a-b). The distance between the roads is greater than the width of the nozzle tip, which creates gaps between the roads.
The CubeX fill layers are composed of roads angled at 45°. However, unlike with the Dimension, these roads do not change orientation between subsequent layers (Figure 9). Instead, the road geometry is the same on all internal layers. This could cause an even more pronounced fracture behaviour than was seen in the Dimension parts.

The Makerbot fill road orientation differs in that the roads were not oriented at 45°, but rather at 0° and 90°. However, like the Dimension, the orientation of the roads did alternate between subsequent layers. The only different layer in the software was the second from the bottom, which had a grid-like pattern (Figure 10). Without physically printing the part, it is impossible to verify the trajectories of the roads on this layer.

3.2.3 Surface Layers

Perimeter road trajectories give clean finishes to vertical walls of printed parts, but surface layers give clean finishes to the top and bottom horizontal surfaces. Surface layers usually have a different road pattern than the internal fills.

The Dimension printer was found to have one surface layer on the bottom and one on the top. These layers had more closely spaced roads than the fill layers (Figure 8c). Even though the layers are closer together, the roads continue to follow the alternating 45° and 135° pattern in the rest of the part. This gives a smoother finish to the part because there are fewer gaps between layers. However, this can lead to a false impression that the internal structure is just as dense as the surface.

The CubeX also has distinct surface layer patterns, but unlike the Dimension, it has four on the top and four on the bottom. There is more variation between these layers and the fill layers than with the Dimension. While the fill of the structure is oriented at 45°, the bottom four layers are all oriented at 0° relative to the horizontal (Figure 11). The top and bottom surface layers are not identical either. Unlike the bottom layers, which repeat at 0°, the top four layers alternate between 0° and 90° (Figure 12).

The Makerbot does not have any noticeable surface layers. The top and bottom layers follow the same alternating 0° and 90° road pattern and spacing throughout the part.

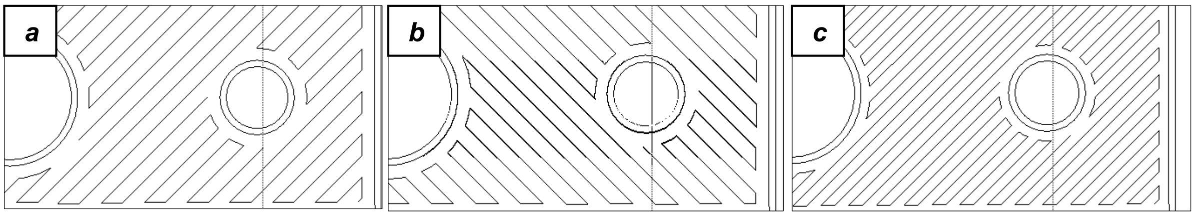


Figure 8. StratasysEX layers alternate between 45° and 135°: a) middle layer orientation b) successive layer c) Top layer with closer spacing between deposition paths

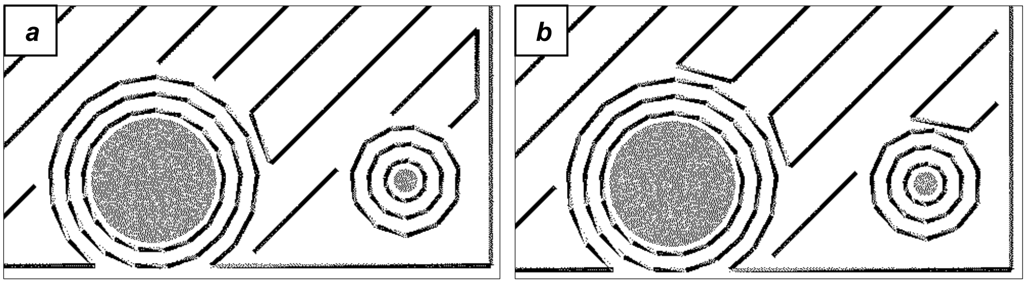


Figure 9. Cubify middle layers at 45° do not alternate deposition angles between layers a) a middle layer b) successive middle layer

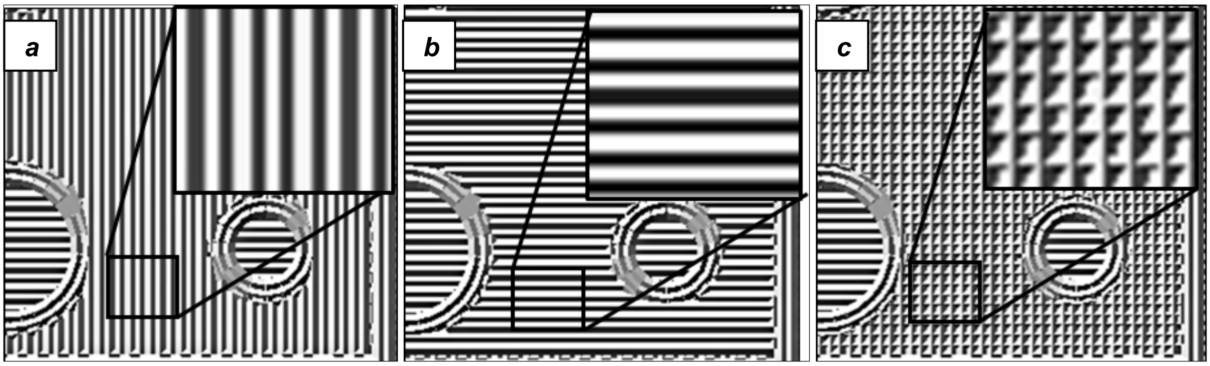


Figure 10. Makerbot Desktop layers alternate between 0° and 90° with only one exception: a) a middle layer b) successive layer c) 2nd layer with grid-like pattern

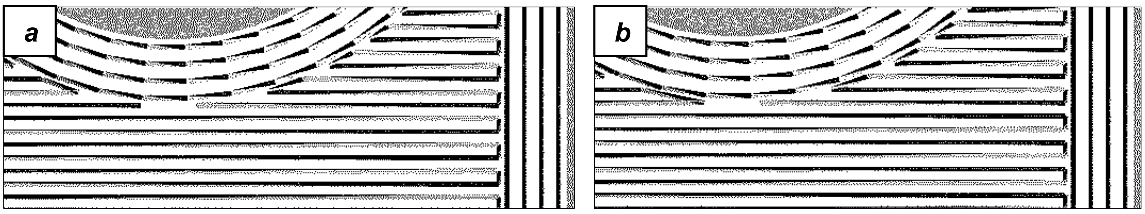


Figure 11. Bottom layers do not alternate deposition angles a) bottom layer b) 2nd layer

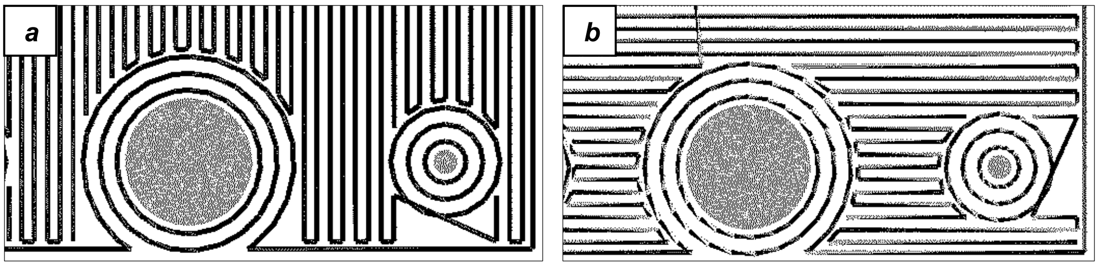


Figure 12. Top layers alternate between 0° and 90° a) top layer b) successive layer

Table 2. Summary of differences Printer Properties

Printer	Perimeter Roads	Surface Layers	Fill Road Orientation
Dimension	2	1	Every layer alternates
CubeX	3-4	4	Top 4 layers and between 4th and 5th
Makerbot	User-defined	0	All layers except 2nd from bottom

4 POROSITY ANALYSIS

It is clear from previous figures and diagrams and text, that different fill road trajectories create different kinds of voids within a single cross-section of the part. Figure 13b shows a cross-section of the test block as fractured in Figure 13a. This surface will be used to discuss voids. There are multiple road patterns visible, so the cross-section was divided into the four parts labelled in the Figure. The "Rectangle Perimeter" and "Hole Perimeter" areas are the vertical walls where the perimeter roads traced out the rectangle and the circle, respectively. The two parallel roads have very small voids because there is no angle altering between deposition layers. The "Internal Area" denotes the fill road layers within the part. The voids here are larger due to the greater distance between roads as was seen in Figure 2.

The "Gap Area" shows an interesting phenomenon of the block geometry. In this particular cross-section, there is a repeating pattern in the fill roads parallel to the perimeter roads. There is a road attached to the rectangle perimeter road, then a gap, and then another road, and so on. The width of the part in this cross-section is not enough to create the four perimeter roads (two for the rectangle and two for the circle) and a fully repeated set of fill roads parallel to them (Figure 14a). Therefore, the perpendicular roads do not have adequate support on the right side, and droop down due to gravity. If a part were optimized for the Dimension printer, all the thicknesses would be a factor of this repeating pattern (Figure 14b).

An analysis was carried out to determine the porosity of the structure. The cross-section from Figure 13 was taken as the basis for this analysis. The image was scaled up so that measurements could be made more precise. The porosity analysis was done by finding the areas of voids in the cross-section and dividing by the total area of the cross-section. Since the largest gaps occurred in the "Gap Area," a second analysis was done assuming that a part was optimized for this Dimension printer. This would mean that the part would be narrowed to a width that would allow the fill road pattern to repeat fully (Figure 14b). The results of this analysis are shown in Table 3. Even if part porosity is expected, the geometries of the roads can still lead to unexpected anomalies such as the Gap Area.

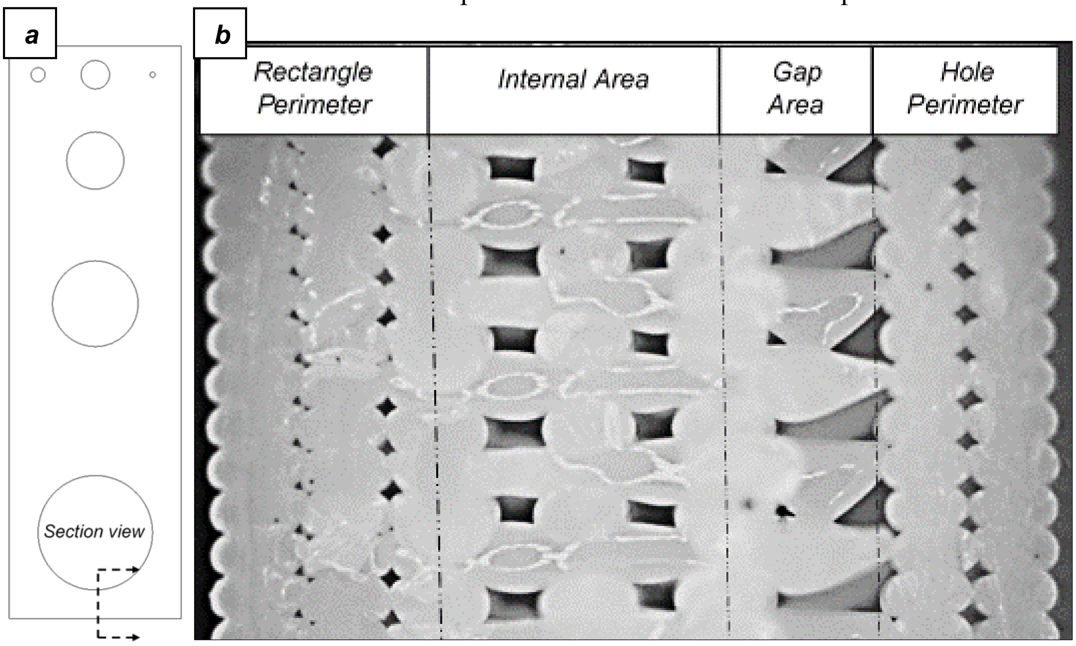


Figure 13. Cross-sectional area across the section between the outside perimeter (left) and the largest hole perimeter (right). On the right, the Gap Area shows the area where there is minimal adhesion between the fill roads and the hole perimeter roads

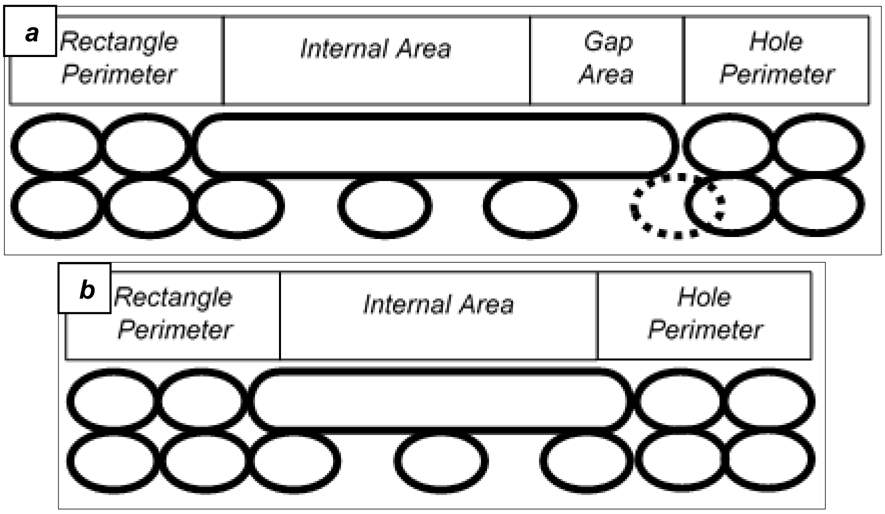


Figure 14. a) Sketch of cross-sectional area showing how the perimeter roads prevent placement of additional fill road. The dotted ellipse shows where a fill road should go for the pattern to repeat fully b) Sketch of a cross-sectional optimized for the Dimension printer

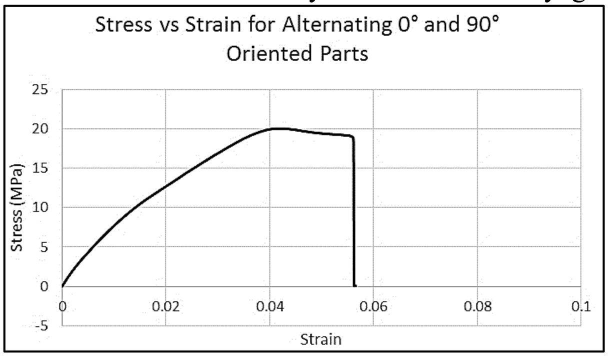
Table 3. Porosity Analysis Results

	Rectangle Perimeter	Internal Area	Gap Area	Hole Perimeter	Actual Cross-Section	Optimized Cross-Section
Total Area	6480 mm^2	8040 mm^2	4440 mm^2	4680 mm^2	23,640 mm^2	21,000 mm^2
Void Area	126 mm^2	708 mm^2	730.5 mm^2	126 mm^2	1780.5 mm^2	960 mm^2
Porosity	1.94%	8.81%	16.45%	2.69%	7.53%	4.57%

5 TENSILE TESTING

Tensile test were used to see the effects of deposition paths on part properties. The test coupons were made using the Dimension sst 1200es printer. Three coupons were made with layer road orientations alternating between 0° and 90° and another three were made alternating between 45° and 135° orientations. The Ahn et al. (2002) paper showed that using the traditional dog-bone-shaped coupons would lead to higher stress concentrations in printed parts, so rectangular coupons were used per the paper's suggestion. The dimensions of the coupons were 9.53 x 6.35 x 50 mm. The coupons were elongated at a speed of 2 mm/min.

The results of the testing showed interesting relationships between the differently oriented parts. The stress-strain curves of both orientations are almost identical in the elastic region (Graph 1). Both show a Young's Modulus of about 500 MPa at 4% elongation. However, the major difference occurs in the plastic region of the graph. The alternating 45° and 135° orientated parts had an elongation of about 9% at the break point, compared to the 5.5% elongation of the alternating 0° and 90° oriented parts. Because of this elongation, the maximum tensile stress was slightly higher. These results follow the same trend as was found by Onwubolu and Rayegani (2014).



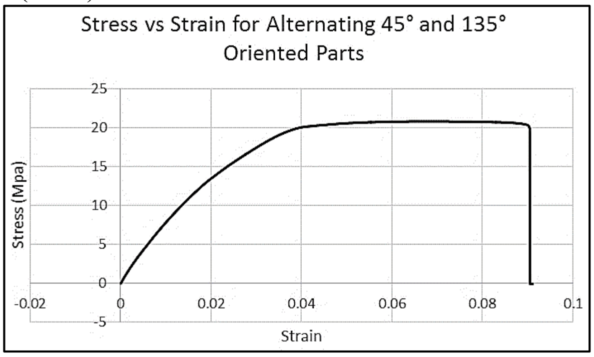


Figure 15. Stress vs Strain graphs from tensile testing on rectangular coupons

The similarity in yield strength, but not in ultimate strength, provides insight into the impact different road geometry has on part properties. Since perimeter roads are independent of build orientation their geometry does not contribute to the differences in the results. In addition, the close spacing of the perimeter roads will cause them to carry a higher percentage of the total load. This is likely the cause of the similarity between Young's moduli. The elastic load is carried by the perimeter roads until the yield point, and plastic elongation starts as the fill roads begin to carry more of the load. In the layer patterns of alternating 0° and 90° roads, only the roads parallel to the load direction will carry a significant portion of the load, while the alternating 45° and 135° roads will share the load evenly. This is consistent with the test results, since the layers with alternating 45° and 135° orientations part showed a higher maximum stress as well as a longer elongation at the break point.

6 FUTURE WORK AND CONCLUSIONS

We created a sample block part in order to explore the differences between printers and software. This exploration yielded interesting results in both the software and in the physical parts. In order to fully understand the implications of our findings, we plan on creating and testing multiple parts for performance characteristics. In addition, a more accurate porosity analysis could be achieved through the use of digital image processing techniques.

The preliminary tensile tests showed differences between parts printed with different road patterns and layer repetitions. To further investigate the effects of different geometry on part properties, we will design a series of test parts, varying the road geometry within layers. This will allow us to compare the relative effects each parameter will have on the overall part. We will also explore at what scales the perimeter roads stop being the major load bearers within the part.

With the initiatives taking place across the country in the expansion of AM technology, it is clear that its use will continue to expand into the foreseeable future, especially in educational settings. This makes it all the more urgent to expose the “hidden” aspects of the process. Another approach suggested to the authors is to follow the precedent set by CNC machining for all builds, in which the deposition path could be generated by the software, but altered manually by the user. Some of the newer commercial models offer this possibility, but it is not standardized like CNC G-Code, and is not currently available for the lower end machines common in academia.

Traditional machining has led to a mind-set of developing design rules for manufacturing that will not be sufficient for FDM. The next generation of users must be made aware that there is no “standard” process in FDM. The design and the manufacturing process include more hidden variables than found in traditional machining (e.g., material removal methods). Understanding these hidden constraints is the only way for FDM to reach its full potential.

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